APPLICATION OF THE HEAT BALANCE APPROACH TO MAXIMUM TEMPERATURE FORECASTING

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ABSTRACT

The daily net energy available for heating the air from 0300 GMT to the following afternoon, as determined by Myers, is used to compute objectively the maximum temperature expected under static, clear-sky conditions at 12 cities in the power distribution area of the Tennessee Valley Authority. The maximum temperatures thus obtained are plotted and analyzed to resolve irregular features of the isotherm patterns. The analysis is then adjusted subjectively primarily for the effect of temperature advection but also for cloudiness, precipitational cooling, and vertical motion—to take account of changes expected by mid-afternoon of the current day and also of the following day. Verification results for seven cities in the TVA area during 1954 and 1955 are presented. The current-day forecast errors are approximately 50 percent less than persistence forecast errors.

1. INTRODUCTION

Myers [1, 2] investigated the local heat balance under clear-sky conditions at Nashville, Tenn., for the five energy transfer processes, insolation, long-wave radiation, ground heating, reflection, and evaporation. His results included a computation of the annual march of the net energy available for heating the air from the time of the 0300 GMT raob to the average time of occurrence of the maximum temperature during the following afternoon.

As a check against these values, Myers made independent estimates of the clear-sky heat balance directly from the Nashville raob data. This was done by first constructing a hypothetical midafternoon sounding based on the maximum temperature for the day and upon the previous 1500 GMT raob and then measuring the heating or cooling from one raob to the next.

The heat-balance values that Myers thus obtained by two different methods showed satisfactory agreement for the period 0300 to 2100 GMT, and particularly for the period 1500 GMT to 2100 GMT, the period of greatest heating during the day. As a final refinement, mean values of the data obtained by the two methods were computed. (See Myers' [2] figure 12 in the preceding article.)

Since these values represent the daily net energy available for heating the air between the time of the 0300 GMT raob and the following afternoon, they can be utilized in determining objectively the maximum temperature that would occur under static, clear-sky conditions. Subjective adjustments for expected thermal changes in the lower atmospheric air column are then applied in making the actual maximum temperature forecast. The Weather Bureau Airport Station at Knoxville has used this approach since 1948 in the preparation of its 12- and 36-hour maximum temperature forecasts for 12 cities in the TVA power distribution area. This paper describes the procedure used in this application of the heat-balance method to maximum temperature forecasting and summarizes the results obtained over a period of 2 years.

It is emphasized that the procedure described represents an actual forecasting operation subject to both time and personnel limitations. Obviously, refinements of the application could be achieved if these limitations were relaxed.

2. DESCRIPTION OF FORECASTING PROCEDURE

The first step in the maximum temperature forecasting procedure is to plot on a pseudoadiabatic chart (WB Form 1147) the 0300 GMT soundings for all raob stations in and around the TVA power distribution area. The appropriate heat energy, as determined by Myers, then is added graphically as a triangular area to the lower portion of each sounding (fig. 1). A transparent overlay (fig. 2), developed by Myers and slightly modified by this office, is used to make the graphical addition. The permanent lines on the overlay are marked lightly, while the line in current use is heavily overwritten with ink to stand out distinctly and prevent confusion. Dates for change in areas, to the nearest fifth day, are shown on the overlay. With the overlay applied to the sounding, as illustrated in figure 1, the clear-sky maximum temperature is determined.

The maximum temperatures thus obtained are plotted on a convenient map base and isotherms drawn at 2° F. intervals. Considerable care is taken to make the isotherm analysis consistent with the 850-mb. constant pressure chart, and the 1,000–850-mb. thickness chart, which is prepared locally for other uses. In addition, past winds at all levels through the heating layer and the maximum temperatures observed the previous day are considered in resolving irregular and unusual isotherm patterns.

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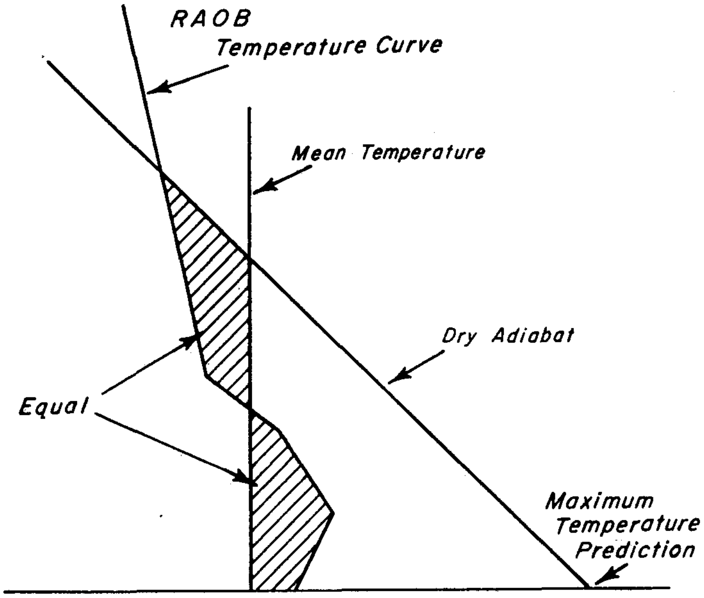

FIGURE 1.—Method used in determining the clear-sky maximum temperature from the raob. (After Myers [2].)

The resulting analysis is a mapped forecast of the maximum temperature that may reasonably be expected under static clear-sky conditions. The next step is to forecast the changes that will take place in the isotherm pattern by midafternoon of the current day and also of the following day.

Expected advection accounts for most of the changes in the forecast isotherm pattern, although cloudiness, precipitational cooling, and vertical stretching and sinking are recognized as important. The advective adjustment is principally subjective in application but is based primarily on the wind expected at gradient level during the forecast period. As a general rule, the isotherms are moved a distance equal to approximately 60 to 80 percent of the wind component normal to the isotherms.

Linear extrapolation of 24-hour thickness change centers on the 1,000–850-mb. chart serves as a check on the logicality of the advective adjustment. A thickness change of 8.7 gpft. in the 1,000–850-mb. layer is equal to a change of 1° F. Disagreement between location of the isotherms by extrapolation and location by the advective method usually indicates that vertical motion will be of considerable importance and that the 60-to 80-percent normal wind advective component will not be reliable. In such cases, an attempt to evaluate the effect of vertical motion is made by compromising the isotherm location between that indicated by advection and by extrapolation. As the advected isotherm pattern location becomes less and less reliable, the greater becomes the anticipated vertical motion.

No general rules can be stated for isotherm adjustments made for cloudiness, and precipitational cooling. Application of adjustments for these factors varies considerably from forecaster to forecaster and is almost completely subjective, although the ratios of insolation with overcast sky to insolation with cloudless sky presented by Haurwitz

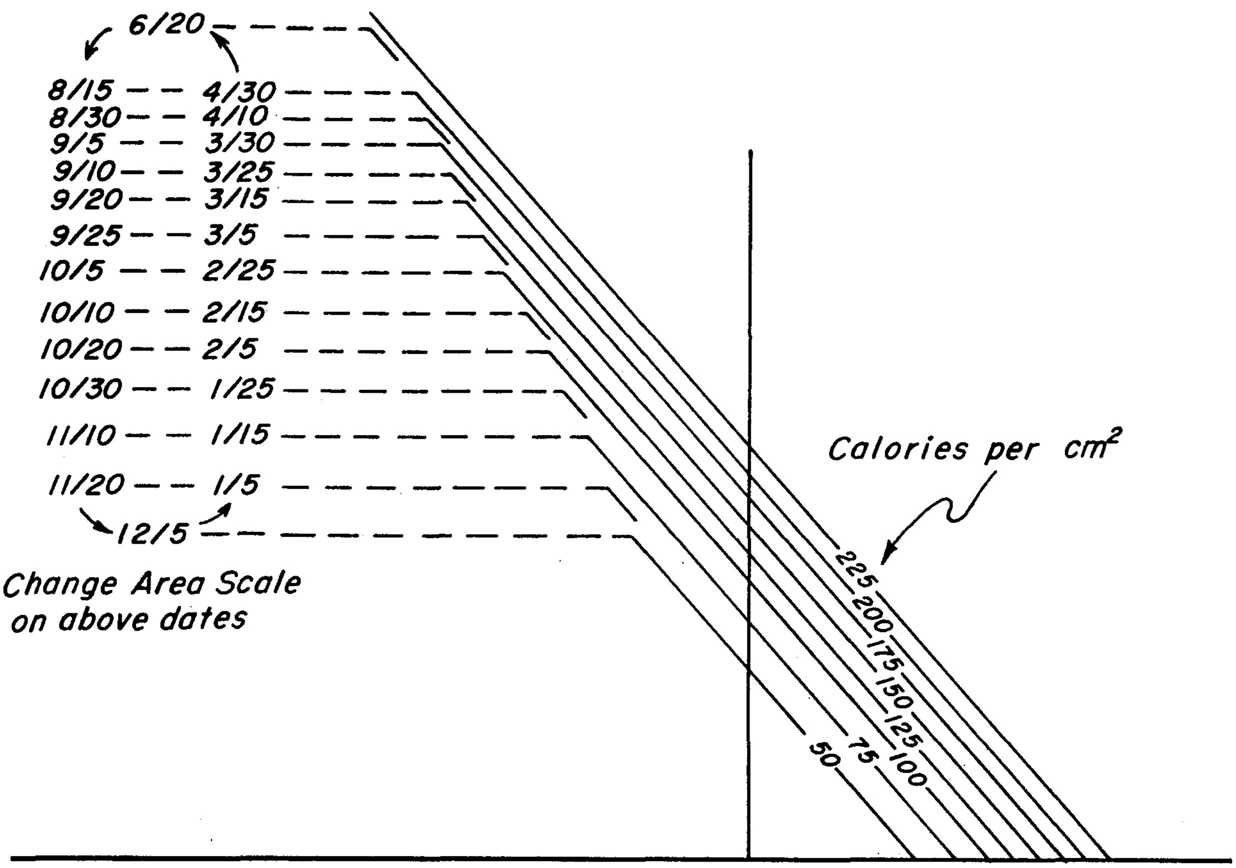

FIGURE 2.—Overlay for WB Form 1147 for graphical addition of net heating to Nashville, Tenn., 0300 GMT raob.

TABLE 1.—*Mean absolute error (° F.) in current-day maximum temperature forecasts and comparison with errors in persistence forecasts, by months. Data period 1954 and 1955*

Station (WBAS)	Mean error in ° F.											
	January	February	March	April	May	June	July	August	September	October	November	December
Birmingham, Ala.:												
Actual	4.2	3.5	3.1	3.0	2.2	2.3	1.9	1.9	2.5	2.6	2.6	3.8
Persistence	7.8	8.3	7.7	5.3	3.7	3.1	2.6	2.4	3.4	5.3	7.2	6.9
Bowling Green, Ky.:												
Actual	4.1	3.8	3.2	3.2	3.0	2.5	1.9	2.6	3.0	2.7	3.0	2.9
Persistence	8.0	9.1	8.1	7.1	5.1	4.4	3.3	5.0	4.4	5.0	7.7	7.0
Bristol, Tenn.:												
Actual	3.4	3.8	3.6	3.0	2.7	2.3	1.7	2.3	2.5	2.1	3.2	3.4
Persistence	6.4	9.9	8.5	5.9	4.8	4.0	2.7	3.5	4.1	4.9	6.7	7.3
Chattanooga, Tenn.:												
Actual	3.8	3.5	3.5	3.1	2.5	2.0	2.0	2.3	2.6	2.5	3.3	3.8
Persistence	6.3	7.1	7.3	6.2	4.6	3.6	3.0	3.0	4.0	5.1	6.7	5.4
Knoxville, Tenn.:												
Actual	3.8	3.3	2.9	2.8	2.8	2.6	1.9	2.7	2.4	2.4	2.7	3.5
Persistence	6.0	8.2	8.4	5.7	4.6	4.3	3.2	3.5	3.7	5.1	6.9	6.2
Memphis, Tenn.:												
Actual	3.6	3.7	3.3	4.0	2.9	2.2	1.9	2.0	2.3	3.2	3.3	3.3
Persistence	7.6	8.3	8.2	6.0	4.5	3.3	2.6	2.8	3.8	5.0	7.2	7.7
Nashville, Tenn.:												
Actual	3.9	3.8	3.4	3.7	2.5	1.7	1.9	2.4	2.7	2.6	3.1	2.8
Persistence	8.5	9.5	8.7	6.3	4.8	3.7	3.1	4.6	4.5	5.4	7.5	7.5
All stations:												
Actual	3.8	3.6	3.3	3.3	2.7	2.2	1.9	2.3	2.6	2.6	3.0	3.4
Persistence	7.2	8.6	8.1	6.1	4.6	3.8	2.9	3.5	4.0	5.1	7.1	6.9

[3] have been helpful in making adjustments for cloudiness. A more objective determination of the alterations to be made to the isotherm pattern resulting from these influences is desirable, but, in general, subjective forecast adjustments seem to be as successful and far less time consuming than any objective methods that we know of.

3. VERIFICATION RESULTS

Monthly verification results of current-day maximum temperature forecasts for seven Weather Bureau Airport Stations are given in table 1. Verification records were not available for the other five cities included in the forecast service.

Table 2 presents the verification results by seasons. The seasonal grouping of months is based on error frequency distributions. While this paper deals primarily with current-day maximum temperature forecasting, second-day maximum temperature forecast verification data in table 3 are given for general informational purposes.

Maximum temperature forecasts for both the current-day and second-day were made at approximately 1230 GMT. Due to TVA operational requirements and procedures, maximum temperature forecasts were not made for a station when the highest temperature was expected to occur early in the day with generally falling temperatures throughout the remainder of the day. All such cases were omitted from the maximum temperature verification data. There was no opportunity for the forecasters to "play the verification system" as the verification system was devised after the basic-data period. Lack of com-

TABLE 2.—*Mean absolute error in current-day maximum temperature forecasts and comparison with errors in persistence forecasts by seasons* [1] *and year. Data period 1954 and 1955.*

Forecasts for:	Source	Mean Error in ° F.				
		Winter	Spring	Summer	Fall	Year
Birmingham	Actual	3.6	2.6	2.2	3.0	2.8
	Persistence	7.9	4.5	2.9	6.4	5.3
Bowling Green	Actual	3.7	3.1	2.5	2.9	3.0
	Persistence	8.4	6.1	4.3	6.5	6.2
Bristol	Actual	3.6	2.9	2.2	2.9	2.8
	Persistence	8.3	5.3	3.6	6.3	5.7
Chattanooga	Actual	3.6	2.8	2.2	3.2	2.9
	Persistence	6.9	5.4	3.4	5.7	5.2
Knoxville	Actual	3.4	2.8	2.4	2.8	2.8
	Persistence	7.6	5.1	3.7	6.0	5.5
Memphis	Actual	3.5	3.5	2.0	3.3	2.9
	Persistence	8.0	5.2	3.2	6.6	5.6
Nashville	Actual	3.7	3.1	2.2	2.8	2.9
	Persistence	8.9	5.5	4.0	6.8	6.2
All Stations	Actual	3.6	3.0	2.2	3.0	2.9
	Persistence	8.0	5.3	3.6	6.4	5.7
		Percent improvement of actual over persistence				
All Stations		55	43	39	53	49

[1] Winter: December–March; Spring: April–May; Summer: June–September; Fall: October–November.

TABLE 3.—*Mean absolute error in second-day maximum temperature forecasts and also a comparison with errors in 2-day persistence forecasts for Knoxville, Tenn. Data period 1954 and 1955.*

Station	Mean error in ° F.												
	January	February	March	April	May	June	July	August	September	October	November	December	Year
Birmingham	6.3	7.0	5.8	4.3	3.7	3.5	2.6	2.9	3.6	4.6	5.6	6.2	4.6
Bowling Green	6.4	7.0	6.6	5.1	4.5	3.7	3.3	4.3	5.2	5.5	6.2	4.5	5.2
Bristol	5.5	7.1	5.7	4.9	4.6	4.1	2.9	3.1	4.1	4.0	4.8	6.2	4.7
Chattanooga	5.2	6.7	4.9	4.8	3.9	3.2	3.0	3.3	3.9	4.6	4.9	5.3	4.4
Knoxville	4.6	5.6	4.9	4.8	4.3	3.5	3.3	3.7	3.9	4.6	4.9	6.1	4.5
2-day persistence	9.3	11.4	11.7	7.7	6.5	5.3	4.1	4.3	5.5	8.0	9.5	9.1	7.7
Memphis	5.9	7.0	6.0	6.0	4.0	3.6	3.0	2.8	4.4	4.9	6.4	5.6	5.0
Nashville	6.7	6.8	6.1	4.9	4.6	3.4	3.1	4.2	4.8	5.6	5.3	5.1	5.0
All stations	5.8	6.7	5.7	5.0	4.2	3.6	3.0	3.5	4.3	4.8	5.4	5.6	4.8

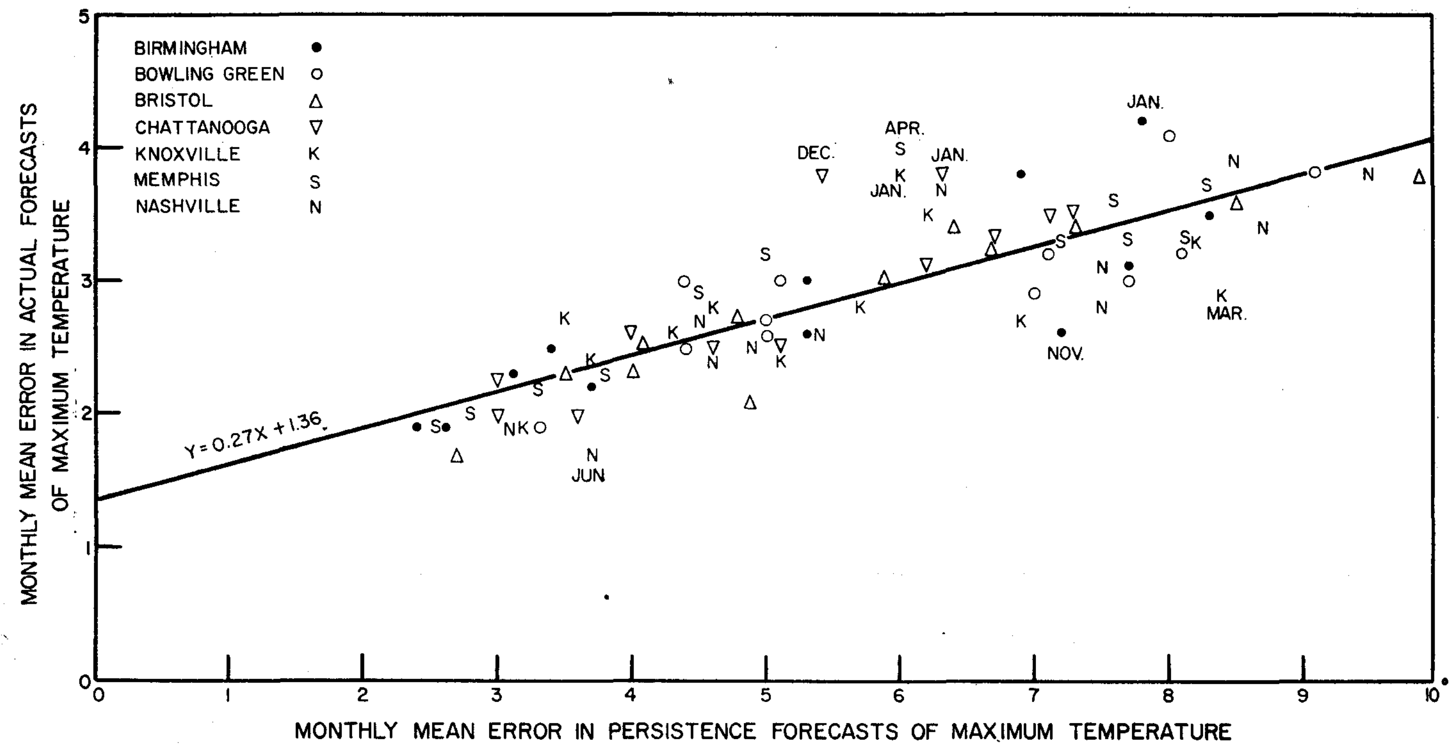

FIGURE 3.—Monthly mean error in actual current-day maximum temperature forecasts plotted against monthly mean error in persistence forecasts for each station, and the regression line for all stations. Data period 1954 and 1955.

parable data arrived at by other practical methods of forecasting maximum temperatures prevented relative evaluation of results. It would have been desirable to compare the actual forecasts with purely objective forecasts based on certain meteorological factors, or combinations of factors, physically related to maximum temperature. However, the preparation of an objective control system would have required considerably more data and time than were available. Therefore, a persistence forecast-control system which required no additional data and which required a minimum of time was selected as most suitable for comparative verification. Under this system, the maximum temperature observed on one day is used as the forecast maximum temperature for the following day. This "blind" persistence forecast system has no forecasting skill. For comparative purposes and to make the absolute error in actual forecasts more meaningful persistence forecast verifications are included in the actual forecast verification in tables 1, 2, and 3.

Several measures of the correspondence between forecast and observed maximum temperatures were computed. These are described here to assist in interpreting the forecast results. The mean or average error was computed for both the actual and persistence forecasts. This is the mean difference between forecast and observed maximum temperature, without regard to sign.

Examination of the monthly mean error in table 1 shows that the actual forecasts were superior to the persistence forecasts in all cases. Percent improvement for all stations combined (table 2) ranged from 39 in the summer season to 55 in the winter season. Table 1 shows that actual forecast errors tend to be large when persistence forecast errors are large. This is an expected characteristic and has been examined in more detail through computation of correlation and regression coefficients (see table 4).

Figure 3 compares the actual forecasts with the persistence forecasts and identifies some months that appear to be unusually poor and unusually good. Birmingham–January, Chattanooga–January and December, Knoxville–January, and Memphis–April appear to be exceptionally poor; while Birmingham–November, Knoxville–March, and Nashville–June appear to be exceptionally good. Examination of both the exceptionally poor and good months showed that the subjective adjustments, especially the timing element for advection, cloudiness, and precipitation were of paramount importance in the overall monthly average forecast accuracy. There was no indication of unreliability of the objectively determined clear-sky maximum temperature.

TABLE 4.—*Mean error of actual maximum temperature forecasts as a function of mean error of persistence forecasts. The 12 pairs of mean errors for each station given in table 1 were used to compute the regression coefficients* a *and* b, *and the correlation coefficient* r. *The regression equation is $E=a+bP$, where E is the mean error of the actual forecasts and P is the mean error of the persistence forecasts for the same station and month.*

Station	a	b	r
Birmingham	1.31	+0.28	0.85
Bowling Green	1.38	+0.26	.83
Bristol	1.17	+0.29	.94
Chattanooga	0.99	+0.37	.85
Knoxville	1.83	+0.18	.60
Memphis	1.22	+0.30	.84
Nashville	1.02	+0.30	.88
All Stations	1.36	+0.27	.83

TABLE 5.—*Frequency distribution of errors in actual current-day maximum temperature forecasts for Birmingham, Bowling Green, Bristol, Nashville, and Memphis combined. Data period 1954 and 1955*

		°F. −19 to −17	−16 to −14	−13 to −11	−10 to −8	−7 to −5	−4 to −2	−1 to +1	+2 to +4	+5 to +7	+8 to +10	+11 to +13	+14 to +16	+17 to +19	Total cases
December	No. cases	1		2	5	25	56	85	72	32	13	6	3		300
	Percent	(*)		1	4	9	21	28	20	10	4	2	1		
January	No. cases		2	4	12	33	65	65	48	30	10	2			271
	Percent		1	1	4	12	24	24	18	11	4	1			
February	No. cases			3	17	21	45	78	53	33	16	1			267
	Percent			1	6	8	17	29	20	12	6	(*)			
March	No. cases			3	13	28	74	87	57	22	6	3	2	1	296
	Percent			1	4	9	25	29	19	7	2	1	1	(*)	
Winter	No. cases	1	2	12	47	107	240	315	230	117	45	12	5	1	1, 134
	Percent	(*)	(*)	1	4	9	21	28	20	10	4	1	(*)	(*)	
April	No. cases			1	8	22	67	93	66	18	18	5		2	300
	Percent			(*)	3	7	22	31	22	6	6	2		1	
May	No. cases			1	4	16	99	109	44	22	10	1			306
	Percent			(*)	1	5	32	36	14	7	3	(*)			
Spring	No. cases			2	12	38	166	202	110	40	28	6		2	606
	Percent			(*)	2	6	27	33	18	7	5	1		(*)	
June	No. cases				1	5	52	140	73	23	6				300
	Percent				(*)	2	17	47	24	8	2				
July	No. cases					10	52	157	74	9	2			1	305
	Percent					3	17	51	24	3	1			(*)	
August	No. cases					14	79	123	73	17	2		1	1	310
	Percent					5	25	40	24	5	1		(*)	(*)	
September	No. cases				9	32	91	108	40	9	5	4	2		300
	Percent				3	11	30	36	13	3	2	1	1		
Summer	No. cases				10	61	274	528	260	58	15	4	3	2	1, 215
	Percent				1	5	23	43	21	5	1	(*)	(*)	(*)	
October	No. cases				4	27	62	111	72	17	6		1		300
	Percent				1	9	21	37	24	6	2		(*)		
November	No. cases			1	6	30	73	78	62	21	7				278
	Percent			(*)	2	11	26	28	22	8	3				
Fall	No. cases			1	10	57	135	189	134	38	13		1		578
	Percent			(*)	2	10	23	33	23	7	2		(*)		
Annual	No. cases	1	2	15	79	263	815	1, 234	734	253	101	22	9	5	3, 533
	Percent	(*)	(*)	(*)	2	7	23	35	21	7	3	1	(*)	(*)	

*Less than 0.5 percent.

Second-day maximum temperature forecast verification data in table 3 show that on the average the mean error in the actual forecasts for the second day was about 1½ times that for the current day. On the average, the mean error for 2-day persistence forecasts (Knoxville only) was about 1⅓ times that for the simple persistence forecasts. Percent improvement of actual second-day forecasts over 2-day persistence forecasts for Knoxville was 42. This compares with an improvement of 49 percent for the actual current-day forecasts over simple persistence forecasts at Knoxville.

The root mean square error was another statistic computed in addition to the mean or average error. In the present study, the forecast errors were approximately

TABLE 6.—*Frequency distribution of errors in actual current-day maximum temperature forecasts for all stations combined. Data period 1954 and 1955*

		°F. −19 to −17	−16 to −14	−13 to −11	−10 to −8	−7 to −5	−4 to −2	−1 to +1	+2 to +4	+5 to +7	+8 to +10	+11 to +13	+14 to +16	+17 to +19	Total cases
December	No. Cases	1		3	8	37	82	131	89	41	16	10	2		420
	Percent	(*)		1	2	9	20	31	21	10	4	2	(*)		
January	No. Cases		2	5	18	45	80	91	74	42	16	2			375
	Percent		1	1	5	12	21	24	20	11	4	1			
February	No. Cases			3	21	33	66	115	68	41	20	3	1		371
	Percent			1	6	9	18	31	18	11	5	1	(*)		
March	No. Cases			5	13	36	105	121	79	35	10	3	2	1	410
	Percent			1	3	9	26	30	19	9	2	1	(*)	(*)	
Winter	No. Cases	1	2	16	60	151	333	458	310	159	62	18	5	1	1, 576
	Percent	(*)	(*)	1	4	10	21	29	20	10	4	1	(*)	(*)	
April	No. Cases			1	11	31	98	133	87	29	23	5		2	420
	Percent			(*)	3	7	23	32	21	7	5	1		(*)	
May	No. Cases			1	2	14	113	157	88	37	13	2		1	428
	Percent			(*)	(*)	3	26	37	21	9	3	(*)		(*)	
Spring	No. Cases			2	13	45	211	290	175	66	36	7		3	848
	Percent			(*)	2	5	25	34	21	8	4	1		(*)	
June	No. Cases				1	5	76	194	102	33	8	1			420
	Percent				(*)	1	18	46	24	8	2	(*)			
July	No. Cases					12	74	221	99	15	5			1	427
	Percent					3	17	52	23	4	1			(*)	
August	No. Cases					18	114	171	95	28	5		2	1	434
	Percent					4	26	39	22	6	1		(*)	(*)	
September	No. Cases				5	25	123	165	71	16	6	4	5		420
	Percent				1	6	29	39	17	4	1	1	1		
Summer	No. Cases				6	60	387	751	367	92	24	5	7	2	1, 701
	Percent				(*)	4	23	44	22	5	1	(*)	(*)	(*)	
October	No. Cases			1	4	31	86	165	101	23	9	1	1		422
	Percent			(*)	1	7	20	39	24	5	2	(*)	(*)		
November	No. Cases			2	9	43	98	110	89	31	8				390
	Percent			1	2	11	25	28	23	8	2				
Fall	No. Cases			3	13	74	184	275	190	54	17	1	1		812
	Percent			(*)	2	9	23	34	23	7	2	(*)	(*)		
Annual	No. Cases	1	2	21	92	330	1, 115	1, 774	1, 042	371	139	31	13	6	4, 937
	Percent	(*)	(*)	(*)	2	7	23	36	21	7	3	1	(*)	(*)	

*Less than 0.5 percent.

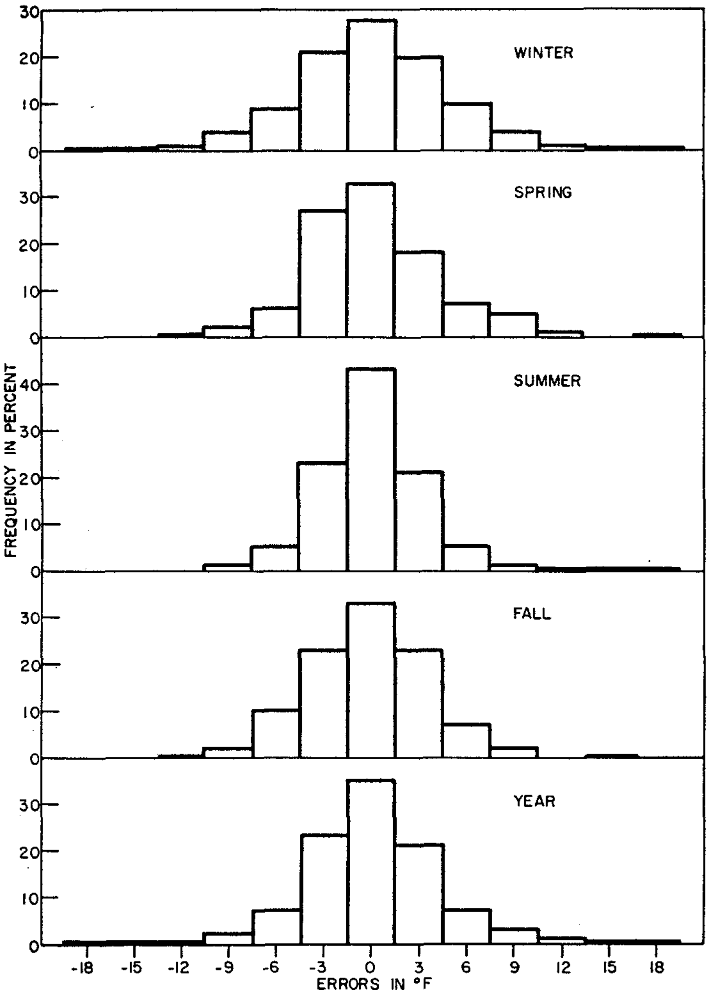

FIGURE 4.—Frequency distribution of errors in actual current-day maximum temperature forecasts for Birmingham, Bowling Green, Bristol, Nashville, and Memphis combined. Data period 1954 and 1955.

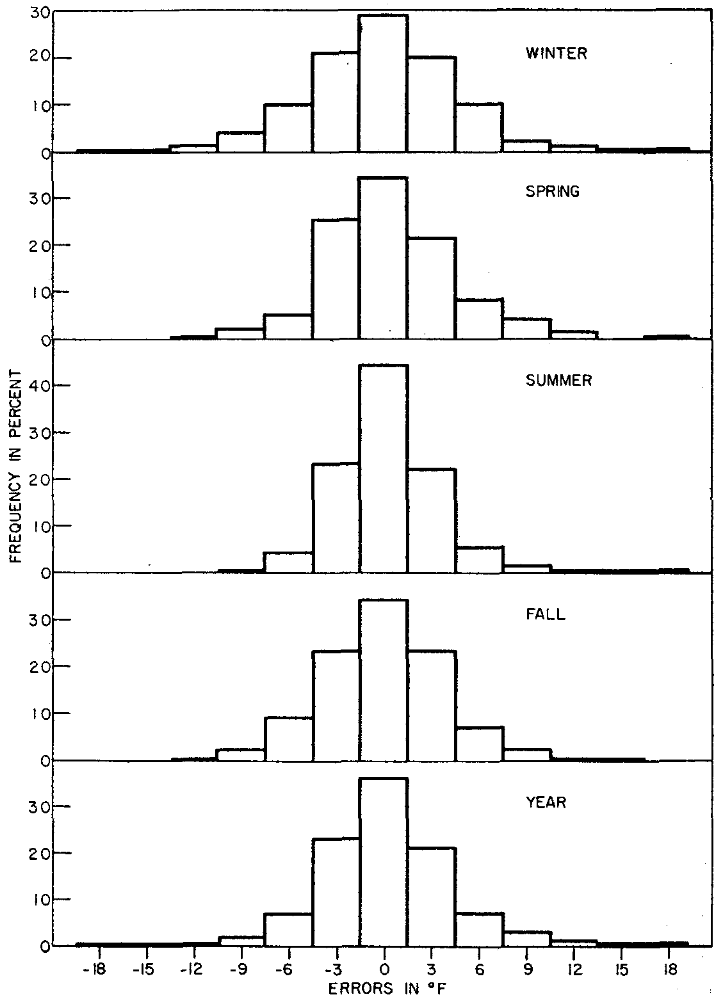

FIGURE 5.—Frequency distribution of errors in actual current-day maximum temperature forecasts for all seven stations combined. Data period 1954 and 1955.

normally distributed and the mean error and root mean square error were highly correlated. Graphical relations between the two statistics suggested that no additional information for ranking purposes could be gained from the use of the root mean square error in addition to the mean error. Graphs of monthly mean error in actual forecasts versus monthly mean error in persistence forecasts indicated that Birmingham, Bowling Green, Bristol, Memphis, and Nashville could be combined in error frequency distributions (table 5 and fig. 4) without appreciable loss of information. All stations were combined in error frequency distributions (table 6 and fig. 5) to provide information of a more general nature to forecasters interested in overall results for all seven stations.

4. SUMMARY

The use of the heat-balance method of maximum temperature forecasting does not require an intimate knowledge of the previous day's weather at each station as does the conventional method of using observed maximum temperatures for the previous day as the forecasting base. In addition, the heat-balance maximum temperature chart with isotherms at 2° F. intervals provides an excellent tool for multiple-station maximum temperature forecasting.

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